Effect of Phosphorus Rates on Growth, Yield, and Postharvest Quality of Tomato in a Calcareous Soil

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Abstract. Phosphorous (P) has a significant role in root growth, fruit and seed development, and plant disease resistance. Currently, no P fertilizer recommendations are available for vegetables grown on calcareous soils in Florida. The objective of this study was to evaluate the impact of different P rates on leaf tissue P concentration (LTPC), plant growth, biomass accumulation, fruit yield, and postharvest quality of tomato (*Solanum lycopersicum* L.) grown on a calcareous soil. The experiment was conducted with soils containing 13 to 15 mg·kg⁻¹ of P extracted by ammonium bicarbonate-diethylenetriaminepentaacetic acid (AB-DTPA). Phosphorus fertilizers were applied at rates of 0, 29, 49, 78, 98, and 118 kg·ha⁻¹ of P before laying polyethylene mulch. Tomatoes were grown using drip irrigation during the winter seasons of 2014 and 2015. No significant responses to P rates were found in LTPC during both growing seasons. Plant height, stem diameter, and leaf chlorophyll content at 30 days after transplanting (DAT) were significantly affected by P rates in 2015, but not in 2014. The responses of plant biomass were predicted by linear models at 60 DAT in 2014 and at 30 DAT in 2015. There were no significant differences in plant biomass at 95 DAT in both years. At the first and second combined harvest, the extralarge fruit yield was unaffected in 2014, but predicted by a quadratic-plateau model with a critical rate of 75 kg·ha⁻¹ in 2015. The total season marketable yields (TSMY) and postharvest qualities were not significantly affected by P rates in either year. Phosphorous rate of 75 kg·ha⁻¹ was sufficient to grow a tomato crop during the winter season in calcareous soils with 13–15 mg·kg⁻¹ of AB-DTPA-extractable P.

Phosphorus is an essential component of nucleic acids, phospholipids, and energy-rich phosphate compounds, thus, it plays crucial role in root growth, fruit and seed development,

and disease resistance. Phosphorus deficiency can stunt plant growth and reduce yield and quality. Over application of P fertilizers, at rates that exceed crop demand, will increase the risk of P losses from soil to water resources and impair water quality through eutrophication (von Wandruszka, 2006). Consequently, appropriate P management is required to maintain crop yield and minimize environmental impacts. In response to the federal Total Maximum Daily Load mandate, the Florida Department of Agriculture and Consumer Services (FDACS) developed Best Management Practices (BMP) for vegetable crops in Florida (FDACS, 2015). One objective of the BMP program is to reduce the environmental impact of crop production on water quality by improving nutrient use

efficiency. Appropriate P fertilization is an important part of the BMP program.

In the United States, FL ranked first in fresh market tomato production with 11,331 ha harvested and a production value of US \$382 million in 2016 (U.S. Department of Agriculture, 2017). Phosphorus recommendations based on preplant soil test P (STP) have been established for tomato grown on acid–mineral soils in Florida (Freeman et al., 2014b). The recommended P rates are 0 and 73 kg·ha⁻¹ when the STP levels are high (>45 mg·kg⁻¹ of Mehlich-3 extractable P or >30 mg·kg⁻¹ of Mehlich-1 extractable P) and low (≤25 mg·kg⁻¹ of Mehlich-3 extractable P) or very low (<10 mg·kg⁻¹ of Mehlich-1 extractable P), respectively (Freeman et al., 2014b).

In Florida, there are 12,000 ha of calcareous soils used for vegetable production (U.S. Department of Agriculture, 2014). However, there are no official STP interpretations based on an effective extractant for calcareous soils. Ammonium bicarbonate-diethylenetriaminepentaacetic acid (Soltanpour and Schwab, 1977), Mehlich-3 (Mehlich, 1984), and Olsen (Olsen et al., 1954) were commonly used as STP extractants in calcareous soils. In Florida, AB-DTPA was adopted with only a sufficient level of 10 mg·kg⁻¹ for vegetable growers (Li et al., 2000). Nonetheless, vegetable growers tend to apply P to avoid fertilizer-related losses of yield and quality even though the STP is higher than that sufficient level. As a result, a large quantity of P accumulates in the soils. Lamberts et al. (1997) found reducing P rates to 37% to 50% of the standard rates used by local vegetable growers had no significant effects on tomato marketable yield. In addition, no yield responses of potato (*Solanum tuberosum* L.) and sweet corn (*Zea mays* L.) were observed in the calcareous soils to P application rates as high as 115 and 80 kg·ha⁻¹, respectively (Li et al., 2000; Olczyk et al., 2003). Thus, P recommendations are not available for tomato grown on calcareous soils in Florida. Therefore, the objective of this experiment was to determine the optimum P rate for tomato production based on LTPC, plant growth, fruit yield, and postharvest quality in a calcareous soil.

Materials and Methods

The study was conducted at the University of Florida (UF)/Institute of Food and Agricultural Sciences (IFAS)/Tropical Research and Education Center, Homestead, FL, during the winter seasons of 2014 (from 29 Oct. 2014 to 24 Mar. 2015) and 2015 (from 15 Oct. 2015 to 16 Feb. 2016). One field (25°30'47"N/80°30'3"W), covered by goosegrass (*Eleusine indica*) over ten years, was selected and plowed, and the grasses were incorporated into the soil (Loamy-skeletal, carbonatic, hypothermic Lithic Udorthents). Sorghum-sudangrass (*Sorghum bicolor* × *S. bicolor* var. *sudanese*) was then planted on 28 Aug. 2014, and the above-ground portions were removed from the field

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on 30 Sept. 2014 for purpose to reduce soil available P concentrations. Soil samples were collected before applying fertilizers in the growing season of 2014 and analyzed for basic physical and chemical properties (Table 1). In the growing season of 2015, preplant Mehlich-3-, AB-DTPA, and Olsen extractable P averaged 51, 13, and 19 mg·kg⁻¹, respectively.

Treatments included 0, 29, 49, 78, 98, and 118 kg·ha⁻¹ of P and were arranged in a randomized complete block design with four replications. Nitrogen (N) and potassium (K) were applied at constant rates of 224 kg·ha⁻¹ of N and 149 kg·ha⁻¹ of K for all treatments. Fertilizer application rates were selected according to the recommendations for tomato grown on acid-mineral soils as well as a previous pot study using the same calcareous soils (Zhu et al., 2016). Tomatoes were grown on bed with drip irrigation. Preplant dry fertilizers, including all P, 56 kg·ha⁻¹ of N, and 56 kg·ha⁻¹ of K, were applied in two bands (15 cm from the center of bed and 8 cm deep). Remaining N and K were supplied weekly from the first flowering to the first harvest stage via drip fertigation following UF/IFAS recommendations (Freeman et al., 2014b). Urea (46–0–0), triple superphosphate (0–46–0), and potassium sulfate (0–0–52) were used as N, P, and K dry fertilizers, respectively. Liquid fertilizers included N-Pact (26–0–0; Loveland Products Inc., Loveland, CO) and LoKomotive (2–0–25; Loveland Products Inc.). Cultural practices used in the experiment were the same in both years except for the dates of fertilization, transplanting, and harvesting (Table 2). The tomato cultivar of Ridgerunner was selected because of its resistance to tomato yellow leaf curl virus, which severely affected tomato production in Florida. The pest control and irrigation management followed UF/IFAS recommendations (Freeman et al., 2014a). After the third harvest in the 2014 season, polyethylene mulch was removed, and tomato plants were incorporated into the soil, then the field was left fallow until the beginning of the 2015 season.

Weather data were obtained from a Florida Automated Weather Network station located 100 m away from the experimental field. Five to six most recently matured whole leaves plus petioles were collected from each plot at 30, 60, and 95 DAT to measure LTPC. Meanwhile, three plants from each plot were selected to measure plant height (from the ground to the tip of the plant), stem diameter (between the third and fourth nodes), and leaf chlorophyll content using the fifth leaf from the apex with a Soil Plant Analysis Development (SPAD) chlorophyll meter (SPAD-502; Konica Minolta Business Solutions Inc., Ramsey, NJ). One whole plant from each plot was also collected at 30, 60, and 95 DAT, and the root, stem, leaf, and fruit portions were separated to measure the dry weight biomass of each part. All plant samples were oven-dried at 70 °C to constant weight. After drying, leaf tissue samples were ground to pass a 0.84-mm sieve, digested by hydrochloric

Table 1. Characteristics of soils collected from the experimental site before applying fertilizers during the winter season of 2014.

Gravel (>2 mm) (%)	63
Clay (%)	3
Silt (%)	5
Sand (%)	29
pH (water)	7.8
Electrical conductivity (μS·cm ⁻¹)	248
Carbonate (g·kg ⁻¹)	379
Organic matter (g·kg ⁻¹)	57
Nitrate-nitrogen (mg·kg ⁻¹)	22
Ammonium-nitrogen (mg·kg ⁻¹)	7
Total P (mg·kg ⁻¹)	1,473
Mehlich-3 extractable phosphorus (mg·kg ⁻¹)	37
Olsen extractable phosphorus (mg·kg ⁻¹)	21
AB-DTPA extractable	15
Phosphorus (mg·kg ⁻¹)	82
Potassium (mg·kg ⁻¹)	6
Iron (mg·kg ⁻¹)	7
Zinc (mg·kg ⁻¹)	11
Manganese (mg·kg ⁻¹)	

AB-DTPA = ammonium bicarbonate-diethylenetriaminepentaacetic acid.

Table 2. Summary of cultural practices used for evaluating phosphorus application rates on tomato grown during 2014 and 2015 winter seasons.

Cultural practice	2014	2015
Plot size	9.1 m length × 5.5 m wide (included three beds)	
Bed spacing (center to center)	183 cm	
Bed height	20 cm	
Bed width	91 cm	
Irrigation type	Drip	
Fumigation	No	
Mulch laying and fertilizer application date	29 Oct. 2014	15 Oct. 2015
Polyethylene mulch	Guardian Standard white on black (Guardian Agricultural Plastics Corp., SC)	
Drip tape	1.6 cm diameter with 20 cm emitter spacing and a flow rate of 4.2 L min ⁻¹ 100 m ⁻¹ at 55 kPa (T-Systems International Inc., CA)	
Tomato cultivar	Ridgerunner (Syngenta, NC)	
Transplanting date	6 Nov. 2014	23 Oct. 2015
Plant spacing	46 cm	
Plant population	11,960 plant/ha	
Harvest unit	10 plants in the middle bed of each plot	
Harvest date	First	25 Feb. 2015
	Second	19 Jan. 2016
	Third	11 Mar. 2015
		2 Feb. 2016
		16 Feb. 2016

acid (Mylavarapu et al., 2014) and analyzed for LTPC through Inductively Coupled Plasma-Optical Emission Spectroscopy (Optima 7000 DV ICP-OES; PerkinElmer Inc., Waltham, MA). Those LTPCs were evaluated according to the adequate range in tomato production (Hochmuth et al., 2012). Tomato fruits were harvested at the mature-green stage at 111, 125, and 138 DAT in 2014 and 88, 102, and 116 DAT in 2015 as the first, second, and third harvest, respectively. Marketable fruits were categorized as extralarge (diameter larger than 7 cm), large (diameter from 6.4 to 7.1 cm), and medium (diameter from 5.7 to 6.4 cm) fruits (U.S. Department of Agriculture, 1997). Unmarketable fruits were recognized based on the presence of the rough blossom-end scar (catface), cracking (concentric and radial), off-shape, zipper scars, sunscald, and other viral and pest damages (Barten et al., 1992; Olson and Freeman, 2016). At the first harvest, ten mature-green fruits from each plot were collected, treated with ethylene and ripened at 20 °C with 85% to 90% relative humidity in DiMare's packing house (Homestead, FL).

After reaching breaker stage, tomatoes were moved out of the packing house and ripened at room temperature (23 to 24 °C) to the table-ripe stage (defined as “the point at which red-ripe tomatoes become noticeably softer when pressure is applied with thumb and fingertips to the equatorial region of each fruit”) for postharvest evaluation (Frasca and Ozores-Hampton, 2014). Fruit firmness was tested as deformation using an 11-mm probe and 1-kg force applied to the fruit equator area for 5 s by a portable digital firmness tester (Model C125EB; Mitutoyo Corp., Aurora, IL); fruit exterior color was measured using a 1 to 6 scale where 1 = green and 6 = red (U.S. Department of Agriculture, 1997); total soluble solids (TSS) at 20 °C, and pH were measured by a portable refractometer (Fisher Catalog Number 13-946-26; Fisher Scientific, Pittsburgh, PA) and a pH meter (Accumet AR 60; Fisher Scientific), respectively.

Leaf tissue P concentrations, plant growth parameters (plant height, stem diameter, and SPAD value), biomass, yield, and postharvest quality assessments were first subjected to a two-way analysis of variance (ANOVA)

using SAS (Version 9.2; SAS Institute Inc., Cary, NC). Year, P rate, and the interaction of year and P rate were included as fixed effects. If the effect of either the year or the interaction was significant, the data from each year were analyzed separately by a one-way ANOVA regarding P rate as the fixed effect. When F test showed statistical significance ($P < 0.05$), the responses to P rates were analyzed by SAS using four regression models: linear, quadratic, linear-plateau ($y = a + bx$ if $x < \text{critical rate}$, $y = \text{plateau}$ if $x > \text{critical rate}$), and quadratic-plateau ($y = a + bx + cx^2$ if $x < \text{critical rate}$, $y = \text{plateau}$ if $x > \text{critical rate}$), where y was the response, x was P rate, and a , b , and c were constants. The best fit model was selected based on $P < 0.05$, lower mean square error, and higher coefficient of determination (r^2) (Ozores-Hampton et al., 2012). The critical rates in linear-plateau and quadratic-plateau models and the rate at which the maximum dependent variable occurred in quadratic model were considered as optimum rates.

Results

In 2014, the average daily 60-cm air and 10-cm soil temperatures from 1 to 30 DAT were 4 °C lower than those in 2015, which were 25 and 27 °C, respectively. From 31 to 60 DAT, the average air and soil temperatures in 2014 were 4 and 2 °C lower than the values of 23 and 24 °C in 2015, respectively. From 61 to 95 DAT, the average air temperature in 2014 was 1 °C lower than that in 2015, and the average soil temperatures were the same between the two years. The rainfall accumulations from 1 to 30 DAT were similar between 2014 and 2015 with 41 and 38 mm, respectively. However, the rainfall accumulations from 31 to 60 DAT and 61 to 95 DAT in 2015 were 26 and 6 times higher than those in 2014, which were 12 and 21 mm, respectively.

Although the interaction effect between year and P rate was not significant for LTPC, the main effect of year was significant, thus, the LTPCs were analyzed separately by year (Table 3). No significant differences were found in LTPC among P rates at 30, 60, and 95 DAT in either year. Without P fertilization,

deficient levels of LTPC were observed at 30 DAT in 2015 and 60 DAT in 2014. Adequate LTPCs were found at 30 and 60 DAT with P rates from 29 to 118 kg·ha⁻¹ in both years. At 95 DAT, LTPCs in all treatments were below the sufficient level of 2 g·kg⁻¹ and averaged 1.6 g·kg⁻¹ in 2014, whereas all the LTPCs were above the sufficient level and averaged 2.5 g·kg⁻¹ in 2015.

The interaction effect between year and P rate was significant for plant height and SPAD value at 30 DAT, and the main effect of year was significant for plant height, stem diameter, and SPAD value at all sampling dates, thus, plant growth data were analyzed separately by year (Table 4). Plant height, stem diameter, and SPAD values at 30 DAT were not significantly affected by P rates in 2014. In 2015, however, those responses were predicted by quadratic-plateau, quadratic-plateau, and quadratic models with optimum P rates of 87, 66, and 78 kg·ha⁻¹, respectively. At 60 DAT, there were no significant differences in those plant growth parameters among P rates in either year. Plant height, stem diameter, and SPAD value at 60 DAT averaged 87 cm, 14 mm, and 55 and 111 cm, 15 mm, and 47 in 2014 and 2015, respectively. No significant differences were found in plant height and stem diameter at 95 DAT in either year. The response of the SPAD value at 95 DAT was predicted by a quadratic model with an optimum P rate of 53 kg·ha⁻¹ in 2014, but in 2015, those values were not significantly affected by P rates.

A significant main effect of year was found for plant (root, stem, and leaf combined), fruit, and total (plant and fruit combined) biomasses, thus, biomass data were analyzed separately by year (Table 5). No significant differences were found in plant biomass among P rates at 30 DAT in 2014. Nevertheless, the plant biomass at 30 DAT increased linearly with increasing P rate in 2015. At 60 DAT, plant and total biomasses increased linearly with increasing P rate in 2014, but not in 2015. The response of fruit biomass at 60 DAT was described by a linear-plateau model with critical P rate of 91 kg·ha⁻¹ in 2014, whereas that response was nonsignificant in 2015. Plant biomasses at 95 DAT were not significantly affected by

P rates and averaged 3424 and 3391 kg·ha⁻¹ in 2014 and 2015, respectively. The proportion of fruit in total biomass at 95 DAT ranged from 53% to 60% and 31% to 39% with an average of 55% and 34% in 2014 and 2015, respectively. In 2014, the fruit and total biomasses at 95 DAT were not significantly affected by P rates. In 2015, however, the responses of fruit and total biomasses at 95 DAT were predicted by linear-plateau and quadratic-plateau models with critical P rates of 64 and 77 kg·ha⁻¹, respectively.

The main effect of year was significant for marketable and unmarketable yield at the three harvests, thus, yield data were analyzed separately by year (Table 6). At the first harvest, extralarge fruits accounted for 90% to 95% and 71% to 86% of the total marketable yield (TMY) in 2014 and 2015, respectively. The extralarge fruit yield and TMY at the first harvest increased linearly with increasing P rate, but no significant differences were found in large and medium fruits and unmarketable yields in 2014. In 2015, the responses of extralarge fruit yield and TMY at the first harvest were predicted by quadratic-plateau models with critical rates of 70 and 78 kg·ha⁻¹, respectively. The large fruit and unmarketable yields at the first harvest of 2015 were significantly affected by P rates, and the responses were described by linear-plateau and linear models, respectively. No significant responses to P rates were found in all the yield categories of the first and second combined harvest in 2014. However, quadratic-plateau and linear-plateau models predicted the extralarge fruit yield and TMY at the first and second combined harvest of 2015 with critical P rates of 75 and 56 kg·ha⁻¹, respectively. At the total season harvest (three harvests combined), the extralarge, large, and medium fruits accounted for 79% to 84%, 12% to 15%, and 4% to 7% and for 23% to 56%, 23% to 35%, and 23% to 43% of TSMY in 2014 and 2015, respectively. All the yield categories at the total season harvest were not significantly affected by P rates and the TSMY averaged 79 t·ha⁻¹ in 2014. In 2015, the extralarge fruit yield increased quadratically with increasing P rate and reached a maximum at 74 kg·ha⁻¹, whereas the medium fruit yield decreased quadratically and reached a minimum at 64 kg·ha⁻¹. No significant differences were found in large fruits yield, TSMY, and unmarketable yield at the total season harvest in 2015 and the TSMY averaged 33 t·ha⁻¹. Neither the interaction effect between year and P rate nor the main effect of year was significant; thus, the data of postharvest qualities from each year were combined for analysis (Table 7). Tomato postharvest qualities, including firmness, exterior color, pH, and TSS content, were not significantly affected by P rates.

Discussion

Leaf tissue P concentrations were not significantly affected by P rates ranging from 0 to 118 kg·ha⁻¹ during the two tomato

Table 3. Leaf tissue phosphorus (P) concentrations in response to P rates for tomato grown in 2014 and 2015 winter seasons.

P rate (kg·ha ⁻¹)	Days after transplanting					
	30		60		95	
	2014	2015	2014	2015	2014	2015
	(g·kg ⁻¹)					
0	2.8	1.9	1.8	2.4	1.6	2.4
29	2.6	2.0	2.0	2.6	1.8	2.5
49	2.9	2.8	2.1	2.3	1.5	2.4
78	2.8	2.5	2.4	2.5	1.7	2.4
98	2.6	2.7	2.9	2.4	1.5	2.5
118	2.7	2.8	2.0	2.5	1.6	2.6
P value	0.76	0.10	0.12	0.17	0.05	0.14
Significance	NS	NS	NS	NS	NS	NS
Adequate range ^z	2.0–4.0		2.0–4.0		2.0–4.0	

^zHochmuth et al. (2012).

NS = nonsignificant.

Table 4. Plant height (cm), stem diameter (mm), and leaf chlorophyll content [represented as Soil Plant Analysis Development (SPAD) value] in response to phosphorus (P) rates for tomato grown in 2014 and 2015 winter seasons.

P rate (kg·ha ⁻¹)	Days after transplanting								
	30			60			95		
	Ht	Diam	SPAD	Ht	Diam	SPAD	Ht	Diam	SPAD
2014									
0	33	8.3	46	86	14	54	118	16	44
29	29	7.0	44	84	13	53	111	15	47
49	35	7.6	45	88	14	55	113	17	48
78	34	8.1	47	91	14	56	115	15	47
98	33	7.6	46	90	14	54	114	16	44
118	32	7.8	48	87	14	55	114	16	43
P value	0.31	0.69	0.08	0.35	0.59	0.58	0.12	0.05	0.01
Significance	NS	NS	NS	NS	NS	NS	NS	NS	*
Regression	—	—	—	—	—	—	—	—	Q
r ²	—	—	—	—	—	—	—	—	0.65
Optimum rate	—	—	—	—	—	—	—	—	53
2015									
0	34	10	44	109	14	47	141	16	43
29	37	10	45	103	14	50	135	15	41
49	53	12	52	117	16	45	140	17	41
78	47	11	49	113	15	47	141	17	41
98	50	11	50	112	18	46	144	17	37
118	51	12	48	110	15	45	150	17	40
P value	0.001	0.01	0.001	0.16	0.05	0.20	0.32	0.48	0.56
Significance	***	**	***	NS	NS	NS	NS	NS	NS
Regression	QP	QP	Q	—	—	—	—	—	—
r ²	0.63	0.46	0.48	—	—	—	—	—	—
Optimum rate	87	66	78	—	—	—	—	—	—

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, and 0.001, respectively.

Q = quadratic; QP = quadratic-plateau; r^2 = coefficient of determination.

Table 5. Plant (root, stem, and leaf combined), fruit, and total (plant and fruit) dry weight biomass in response to phosphorus (P) rates for tomato grown in 2014 and 2015 winter seasons.

P rate	Days after transplanting						
	30		60		95		
	Plant	Plant	Fruit	Total	Plant	Fruit	Total
(kg·ha ⁻¹)							
2014							
0	112	1,192	91	1,282	3,322	3,871	7,193
29	86	908	26	934	3,597	4,153	7,750
49	122	1,321	114	1,435	3,459	4,395	7,854
78	135	1,764	198	1,962	3,070	4,638	7,708
98	135	2,049	270	2,319	3,434	4,137	7,571
118	109	1,549	107	1,656	3,663	4,124	7,787
P value	0.38	0.002	0.001	0.001	0.50	0.43	0.81
Significance	NS	**	***	**	NS	NS	NS
Regression	—	L	LP	L	—	—	—
r ²	—	0.45	0.39	0.43	—	—	—
Optimum rate	—	—	91	—	—	—	—
2015							
0	189	1,959	271	2,229	3,003	1,400	4,403
29	174	1,609	176	1,786	3,208	1,512	4,720
49	299	1,858	234	2,092	3,690	1,809	5,498
78	290	2,136	386	2,522	3,316	2,119	5,435
98	388	2,220	359	2,580	3,174	1,714	4,888
118	349	2,505	794	3,299	3,953	1,803	5,756
P value	0.01	0.30	0.16	0.16	0.12	0.001	0.02
Significance	**	NS	NS	NS	NS	***	*
Regression	L	—	—	—	—	LP	QP
r ²	0.58	—	—	—	—	0.64	0.36
Optimum rate	—	—	—	—	—	64	77

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, and 0.001, respectively.

L = linear; LP = linear-plateau; QP = quadratic-plateau; r^2 = coefficient of determination.

growing seasons. Li et al. (2000) also found P rates from 10 to 116 kg·ha⁻¹ had no significant effect on LTPC of potato in calcareous soils with 57 mg·kg⁻¹ of AB-DTPA extractable P in Florida. Nonetheless, in neutral-mineral soils with very high Mehlich-1 extractable P, LTPCs were shown to increase linearly or

quadratically with increasing P rate from 0 to 99 or 200 kg·ha⁻¹ during tomato growing seasons in Florida (Hochmuth et al., 1999; Shuler and Hochmuth, 1995). Nonsignificant responses of LTPC might be attributed to the limited impacts of P fertilization on soluble P in calcareous soils comparing with

neutral-mineral soils. Dissolved P from fertilizer could be rapidly fixed by surface adsorption and precipitation due to the presence of free calcium carbonate (von Wandruszka, 2006; Zhou and Li, 2001). Because there were limited increases in soil solution P that served as sources for plant uptake, the

Table 6. Effect of phosphorus (P) rates on tomato marketable and unmarketable yield at the first, first and second combined, and total season (three harvests combined) harvests in 2014 and 2015 winter seasons.

P rate (kg·ha ⁻¹)	First harvest					First and second harvest					Total season harvest				
	XL ²	L	M	TMY	U	XL	L	M	TMY	U	XL	L	M	TSMY	U
	(t·ha ⁻¹)														
	2014														
0	39	2.2	0.2	41	8	59	7.6	0.9	68	17	62	11.9	4.5	78	27
29	36	3.7	0.2	40	11	58	8.0	1.2	68	19	61	9.8	5.1	76	29
49	43	3.9	0.2	47	15	57	7.6	0.9	65	25	59	9.7	3.4	72	32
78	48	3.3	0.0	52	13	64	6.7	0.9	72	23	67	9.4	3.7	80	34
98	46	2.9	0.3	49	11	63	6.6	1.7	72	20	66	9.9	4.7	80	27
118	50	4.4	0.4	55	12	70	7.9	0.6	78	20	72	10.3	3.8	86	28
P value	0.05	0.06	0.52	0.03	0.23	0.55	0.55	0.61	0.61	0.41	0.62	0.39	0.60	0.67	0.26
Significance	*	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Regression ^y	L	—	—	L	—	—	—	—	—	—	—	—	—	—	—
r ²	0.31	—	—	0.33	—	—	—	—	—	—	—	—	—	—	—
Optimum rate	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2015														
0	3	0.9	0.1	4	1.5	6	4.4	3.9	14	4.4	7	10.8	13.3	31	7.0
29	6	1.2	0.1	7	1.7	9	3.7	3.1	16	3.9	10	10.3	12.0	33	7.1
49	16	2.6	0.6	19	7.4	17	5.1	2.6	25	9.1	18	7.3	7.3	32	10.8
78	11	2.3	0.7	14	6.5	15	4.6	3.7	24	8.6	16	10.1	10.3	37	11.4
98	13	3.3	0.8	18	5.5	16	6.3	3.2	26	7.5	17	9.0	8.5	34	9.0
118	12	3.4	1.2	17	8.0	15	6.1	3.4	25	10.7	16	9.5	9.5	34	13.1
P value	0.001	0.02	0.08	0.001	0.04	0.001	0.16	0.49	0.001	0.10	0.001	0.23	0.04	0.47	0.24
Significance	***	*	NS	***	*	***	NS	NS	***	NS	***	NS	*	NS	NS
Regression ^y	QP	LP	—	QP	L	QP	—	—	LP	—	QP	—	QP	—	—
r ²	0.57	0.43	—	0.58	0.30	0.65	—	—	0.63	—	0.67	—	0.31	—	—
Optimum rate	70	105	—	78	—	75	—	—	56	—	74	—	64	—	—

²XL = extralarge (>7 cm), L = large (6.4–7.1 cm), M = medium (5.7–6.4 cm), TMY = total marketable yield, U = unmarketable, TSMY = total season marketable yield.

^yL = linear; QP = quadratic-plateau; LP = linear-plateau; r² = coefficient of determination.

NS, *, ***Nonsignificant or significant at $P < 0.05$ and 0.001 , respectively.

Table 7. Postharvest evaluation of tomato fruit firmness (represented as deformation), exterior color, pH, and total soluble solids (TSS) after the first harvest for tomato grown with different phosphorus (P) rates in winter seasons.

P rate (kg·ha ⁻¹)	Deformation ² (mm)	Exterior color ^y	pH	TSS (°Brix)
0	2.8	4.8	4.4	3.7
29	2.5	5.2	4.4	3.7
49	2.5	5.1	4.3	3.8
78	2.8	5.3	4.3	3.7
98	2.5	5.0	4.4	3.8
118	2.6	5.2	4.4	3.9
P value	0.37	0.40	0.22	0.23
Significance	NS	NS	NS	NS

²Firmness test: very firm ≤0.7 mm, firm ≤1.4 mm, medium ≤2.1 mm, soft ≤2.8 mm, and very soft >2.8 mm.

^yExterior color: 1 = green, 2 = breaker, 3 = turning, 4 = pink, 5 = light red, 6 = red.

NS = nonsignificant.

absorbed P was mainly used for biomass accumulation or P accumulation in fruits rather than in leaves; thus, the LTPC did not significantly increase as P rates increased during the growing season.

Carrijo and Hochmuth (2000) found zero P fertilization resulted in deficient tomato LTPC at 88 DAT in acid–mineral soils with either high or very low Mehlich-1 extractable P in Florida. In the present study, deficient LTPC occurred at 60 and 95 DAT in 2014 whereas only at 30 DAT in 2015 for the zero P treatment. At 30 DAT in 2014, adequate LTPC in all treatments in combination with unaffected plant growth parameters and plant biomass indicated that the initial STP concentrations were sufficient for tomato early growth. At 60 DAT in 2014, although there were no significant differences in plant growth parameters, deficient LTPC was

observed in zero P treatment, and the plant biomass increased linearly with increasing P rate. These results showed that with plant growth, additional P was progressively provided by fertilizer sources. Nevertheless, at 95 DAT in 2014, the improvement effect of P fertilization on plant biomass was not significant, and deficient LTPCs were observed in all treatments, suggesting the impacts of P fertilization on LTPC and biomass accumulation did not remain until 95 DAT. These findings were supported by Castro and Torrent (1995), which found that the availability of applied P decreased with time during the growing season. Similarly, Liu et al. (2011) showed that a P application rate of 90 kg·ha⁻¹ increased processing tomato plant biomass (stem and leaf combined) by only 9% comparing with 0 kg·ha⁻¹ at the end of growing season in acid to neutral-mineral soils with

medium to high levels of Olsen extractable P. At 95 DAT in 2014, the decreased SPAD value with P rates higher than 78 kg·ha⁻¹ might be attributed to the reduced uptake and translocation of iron (Fe) as indicated by Mengel and Kirkby (1987).

In 2015, deficient LTPC was found at 30 DAT but not at 60 and 95 DAT for the zero P treatment. In addition, P rates of 0 and 29 kg·ha⁻¹ resulted in significantly lower plant height and leaf chlorophyll content than other rates and plant biomass increased linearly with increasing P rate at 30 DAT in 2015. The crop responses to P rates were affected by the initial STP as well as soil temperature, which influenced soil microbial activity, root metabolism, and P diffusion (Havlin et al., 2005; Potash and Phosphate Institute, 1999b). Thus, the availability of P after fertilization was improved by the higher soil temperature from 1 to 30 DAT in 2015. Meanwhile, the higher plants and larger stem diameters indicated plant growth was faster within the first 30 d in 2015 than in 2014, which was probably due to the higher air temperature. Mengel and Kirkby (1987) revealed that there was a relatively high crop P requirement at early growth stages. Sainju et al. (2003) also concluded adequate P nutrition enhanced early plant establishment of tomato. Therefore, supplemental P at and below 29 kg·ha⁻¹ could not provide as much P as other higher rates for plant growth, and the optimum P rates were predicted to be 66 to 87 kg·ha⁻¹ based on the plant growth parameters at 30 DAT in 2015. According to Raghothama and Karthikeyan (2005) and

Vance et al. (2003), plants have ability to acquire adequate P in P-limiting conditions by modifying root morphology and architecture. As a result, no deficient LTPC and no significant differences were observed in plant growth parameters and plant biomass among P rates at 60 and 95 DAT in 2015.

The deficient levels of LTPC with all P rates at 95 DAT in 2014 were due to the translocation of larger amount of P from leaves to fruits comparing with 2015, which was confirmed by the fruit biomass. At 95 DAT, plant biomasses were similar between the two years, but the fruit biomasses in 2014 were higher than those in 2015 at equivalent P rates. The faster plant growth rate resulted in a 22-d shorter-growing season in 2015 compared with 2014. Yield potential of non-perennial crops could be depressed by shorter life cycle (Hatfield and Prueger, 2015). In addition, higher rainfall accumulation from 31 to 95 DAT adversely affected tomato pollination and fruit development (Ozores-Hampton and McAvoy, 2015). Consequently, the fruit and total biomasses at 95 DAT were lower in 2015 than in 2014. Fruit biomasses at 95 DAT were significantly affected in 2015 but not in 2014, which could be explained by an increased resistance to adverse weather conditions as a result of P fertilization in 2015.

The initial STP levels in this study were categorized as very high and high adopting the AB-DTPA and Olsen interpretations for Colorado calcareous soils (Self, 2000), respectively. Wiedenfeld and Provin (2010) found no yield response of corn (*Zea mays* L.) to P rates ranging from 0 to 73 kg-ha⁻¹ in a calcareous soil with higher than 60 mg·kg⁻¹ of Mehlich-3 extractable P. In addition, P rates of 10 to 116 kg-ha⁻¹ did not significantly affect potato tuber yield in calcareous soils with 57 mg·kg⁻¹ of AB-DTPA extractable P in Florida (Li et al., 2000). Similarly, no significant responses of tomato TSMY to P rates were found in this study. However, there were significant responses at the first harvest of both years. The extralarge fruit yield and TMY at the first harvest of 2014 increased linearly with increasing P rate, which followed the same pattern of total biomass accumulation at 60 DAT in 2014. Carrijo and Hochmuth (2000) also showed linear responses of extralarge fruit yield and TSMY to P rates from 0 to 100 kg-ha⁻¹ in acid-mineral soils with very low Mehlich-1 extractable P. Nonetheless, no significant yield responses were observed at the first and second combined and total season harvests in 2014. These results supported the conclusion that the impacts of P fertilization were limited and could not continue until the late growth stage as discussed previously. In 2015, under adverse weather conditions, P rates as high as 70 to 75 kg-ha⁻¹ increased extralarge fruit yield from the first to the total season harvest, and P rates of 0 and 29 kg-ha⁻¹ resulted in lower extralarge but higher medium fruit yield at the total season harvest. Because the TSMY were not significantly affected, the results indicated the delayed maturity at low

P rates as identified by Potash and Phosphate Institute (1999a). Overall, using the extralarge fruit yield, which brought the highest return to grower (Pernezny et al., 1996), rather than the unaffected TSMY to calibrate P requirement appeared to be practical. Phosphorus recommendation for open field tomato production was reported as 55 kg-ha⁻¹ in calcareous soils with lower than 50 mg·kg⁻¹ of Olsen extractable P (Zhang et al., 2007). In the calcareous soils of this study with extremely high carbonate content, P rate of 75 kg-ha⁻¹ was predicted as sufficient rate based on the extralarge fruit yields in 2015. These rates need to be validated by further studies with more growing seasons and various tomato varieties.

The lack of response of fruit firmness, exterior color, pH, and TSS content to P rates might be due to the sufficient level of initial STP. Liu et al. (2011) showed P rates from 0 to 90 kg-ha⁻¹ had no significant effects on the TSS content of processing tomato in acid to neutral-mineral soils with 37 to 65 mg·kg⁻¹ of Olsen extractable P. Similarly, Oke et al. (2005) found exterior color, pH, and TSS content of processing tomato were not significantly affected by P rates ranging from 22 to 97 kg-ha⁻¹ in sandy loam soils with 30 to 50 mg·kg⁻¹ of STP. Furthermore, in acid-mineral soils with 6 mg·kg⁻¹ of Bray extractable P, 26 kg-ha⁻¹ of P significantly increased tomato pH and TSS content comparing with 0 and 13 kg-ha⁻¹, whereas no significant differences were found among P rates above 26 kg-ha⁻¹ (Adebooye et al., 2006). However, Carrijo and Hochmuth (2000) reported P rates from 0 to 100 kg-ha⁻¹ did not significantly affect tomato pH and TSS content in acid-mineral soils with either high or low level of Mehlich-1 extractable P. Thus, besides preplant STP level, the response of tomato postharvest qualities to P rates might predominantly depend on tomato variety and growing season as revealed by Adebooye et al. (2006) and Hartz et al. (2001).

Conclusions

Results indicated the initial STP levels were sufficient for tomato early growth in 2014. In 2015, irrespective of the adequate initial STP, deficient LTPC was observed without P fertilization and plant biomass increased linearly with increasing P rate at 30 DAT, which could be attributed to the more rapid plant growth rate and higher soil temperature. The optimum P rates were predicted to be between 66 and 87 kg-ha⁻¹ based on the plant growth parameters at 30 DAT in 2015. At 60 DAT in 2014, deficient LTPC was observed in zero P treatment, and plant biomass increased linearly with increasing P rate. Nonetheless, no deficient LTPC and no significant differences were observed in plant biomass among P rates at 60 DAT in 2015. The LTPC, plant height, stem diameter, and plant biomass at 95 DAT were not significantly affected by P rates in both years. The extralarge fruit yield at the first and second combined harvest was not

significantly affected in 2014, but the response was predicted by a quadratic-plateau model with critical rate of 75 kg-ha⁻¹ in 2015. No significant responses of TSMY and post-harvest qualities to P rates were found in both years. Therefore, based on this study, the P rate of 75 kg-ha⁻¹ was considered adequate for tomato production on those calcareous soils.

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